LA-UR-12-26827

Approved for public release; distribution is unlimited.

Title: Stabilizing a laboratory plasma column beyond the external kink limit

Author(s): Sears, Jason A.
Intrator, Thomas P.
Weber, Thomas
Daughton, William S.
Klarenbeek, Johnny
Gao, Kevin W.

Intended for: American Geophysical Union, 2012-12-03 (San Francisco, California, United States)

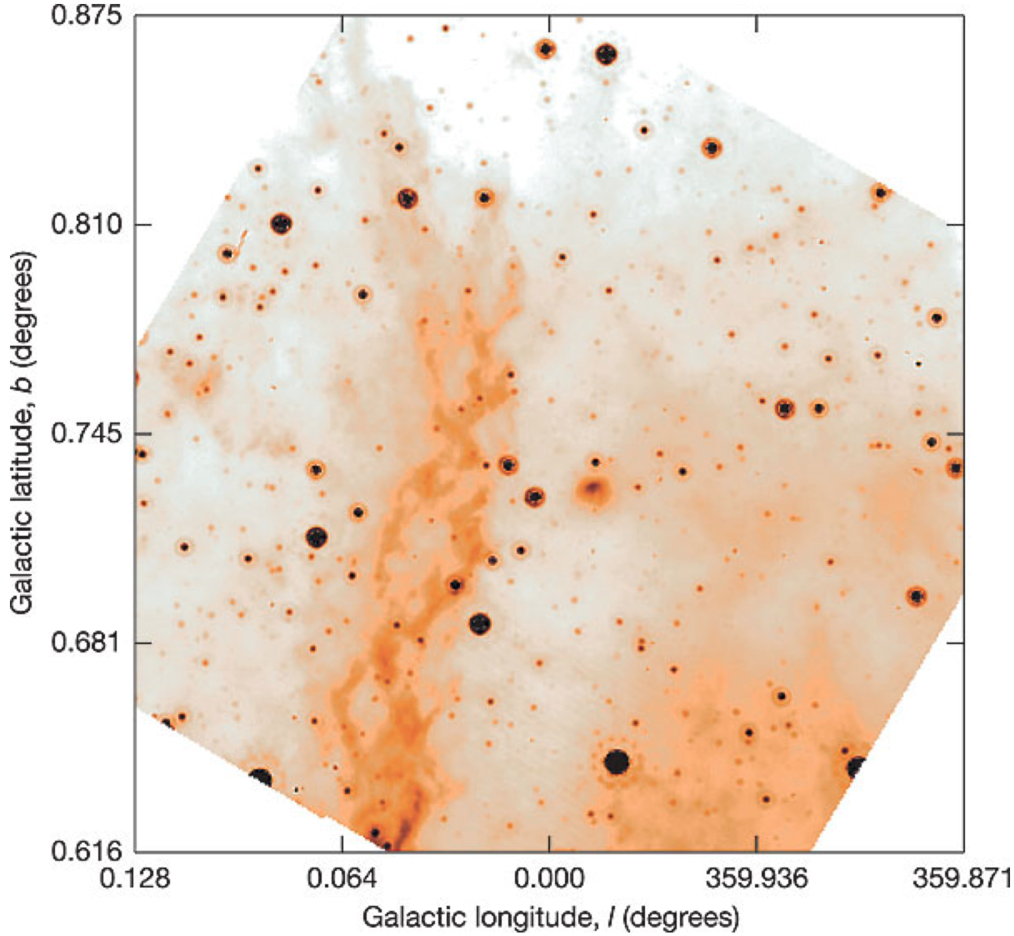
Saturated external kink instability of a laboratory plasma column

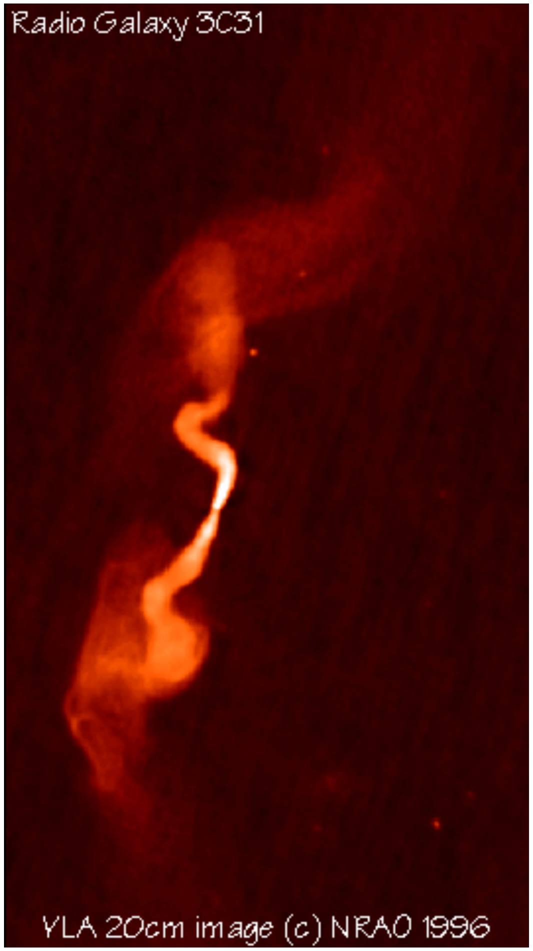
J. Sears, T. Intrator, T. Weber, W. Daughton

J. Klarenbeek, K. Gao

Los Alamos National Laboratory

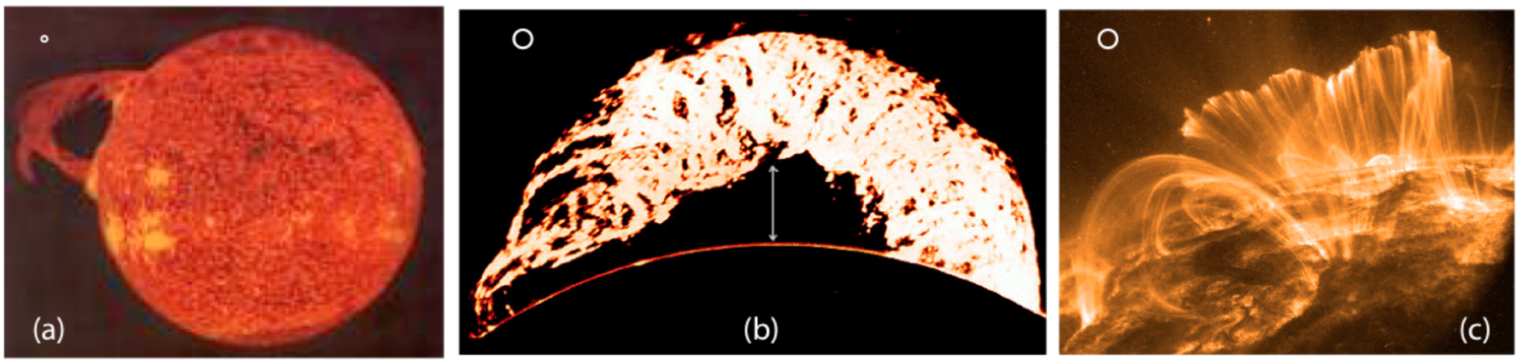
flux ropes in the universe exhibit a kink instability.





Los Alamos

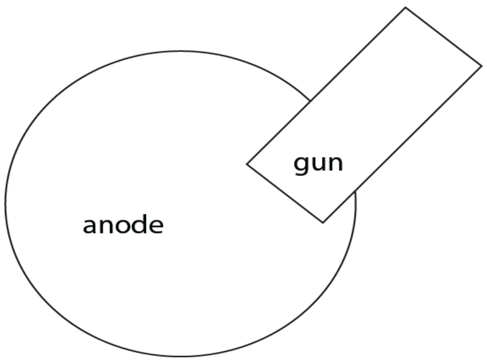
CMEs may also suffer from kink instabilities



the sawtooth in a tokamak is also a kink mode

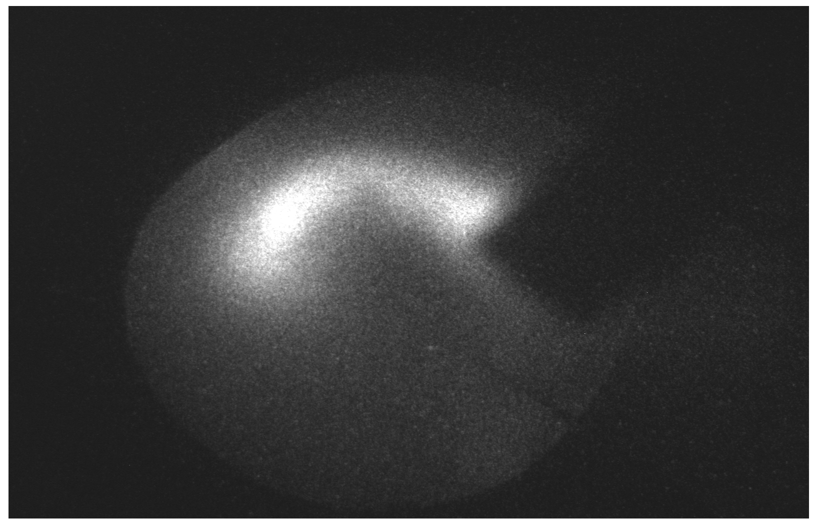
Los Alamos

the RSX current-driven kink mode saturates at finite amplitude



axial perspective

the kink gyrates at a steady rate, indefinitely



do kink instabilities in astrophysical flux ropes also saturate?

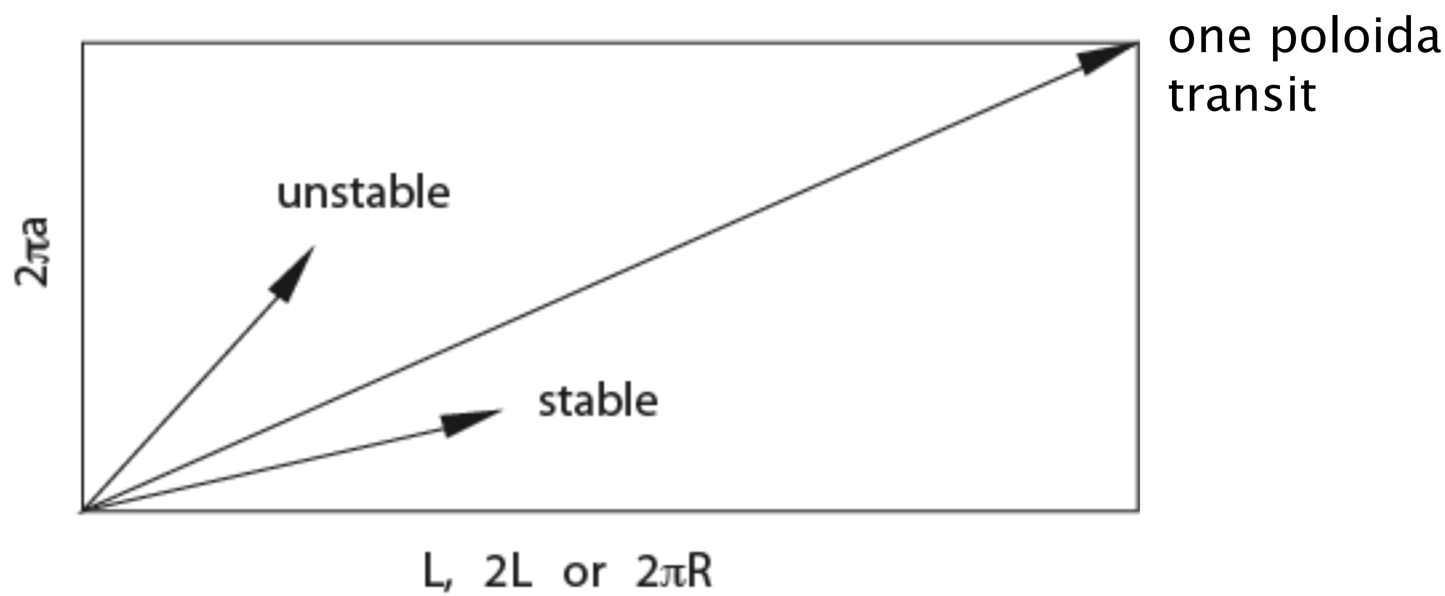
Los Alamos

in this talk:

- potential causes of saturation of the kink instability
- Reconnection Scaling Experiment (RSX)
- 3D measurements suggest current above the kink threshold; present insight

the kink arises when azimuthal magnetic field is too great

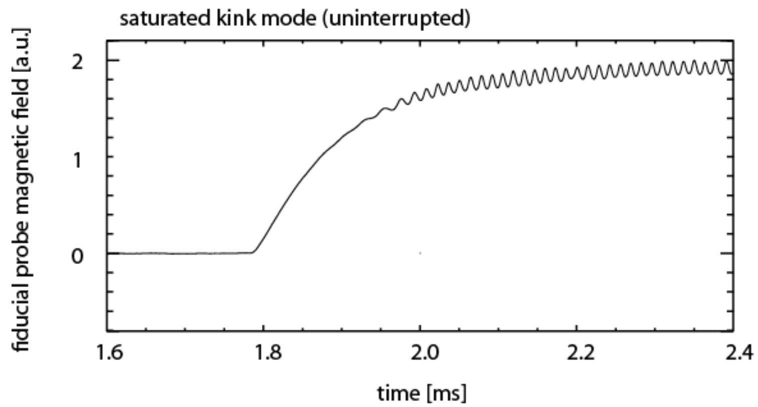
linear model: $$J_{ks} = \frac{4\pi B}{\mu_0 L}$$



the kink handedness is paramagnetic
kink pitch is not constant
flow causes gyration; sense depends on k/|k|

Los Alamos

the kink persists on long timescales



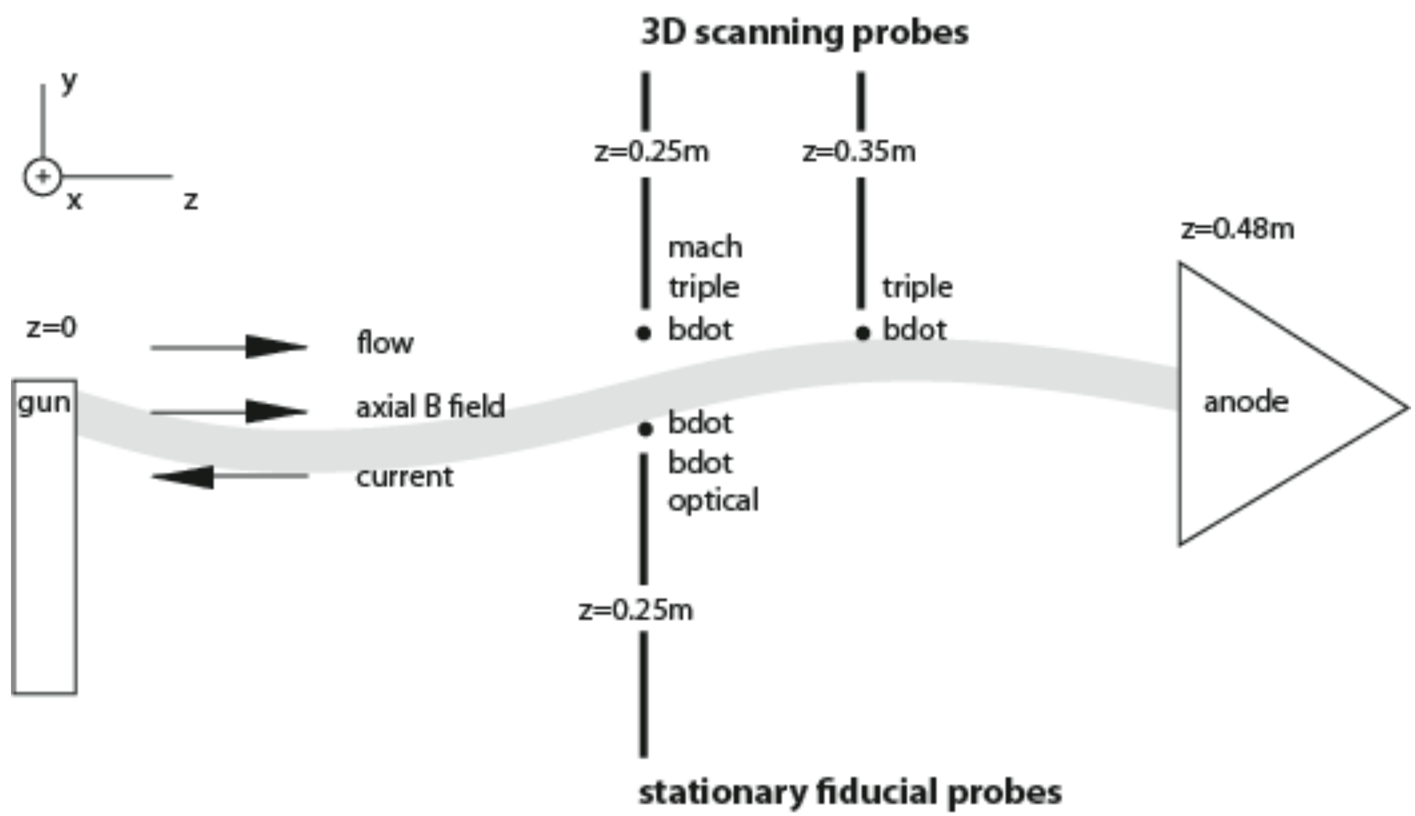
magnetic field perturbation near flux rope after current ramp shows very steady gyration

potential causes of saturation

conductive wall
flow
dynamic stabilization
field-line tension from aperiodicity
non-linear MHD
two-fluid effects
kinetic effects
secondary instabilities, islands, 'gravity'

Los Alamos

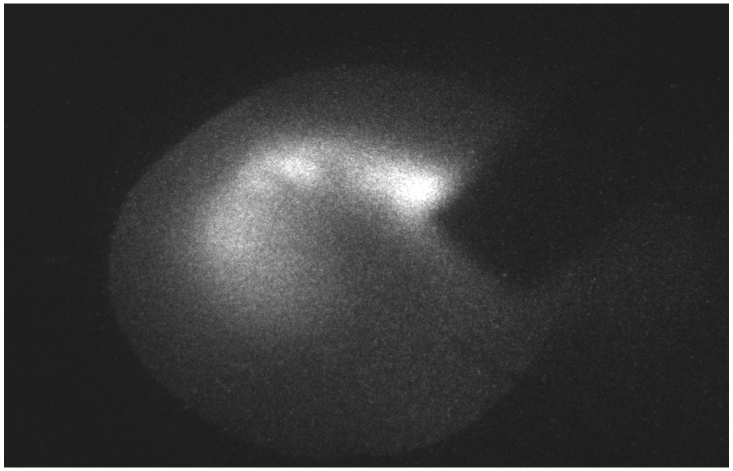
geometry of the gun/anode/diagnostic system

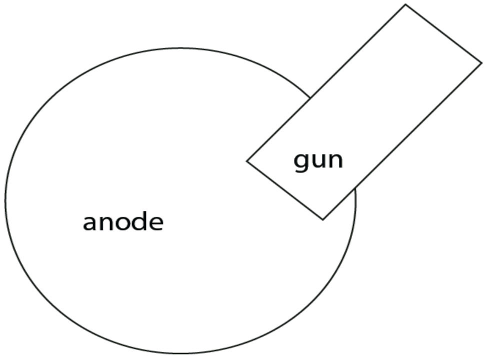


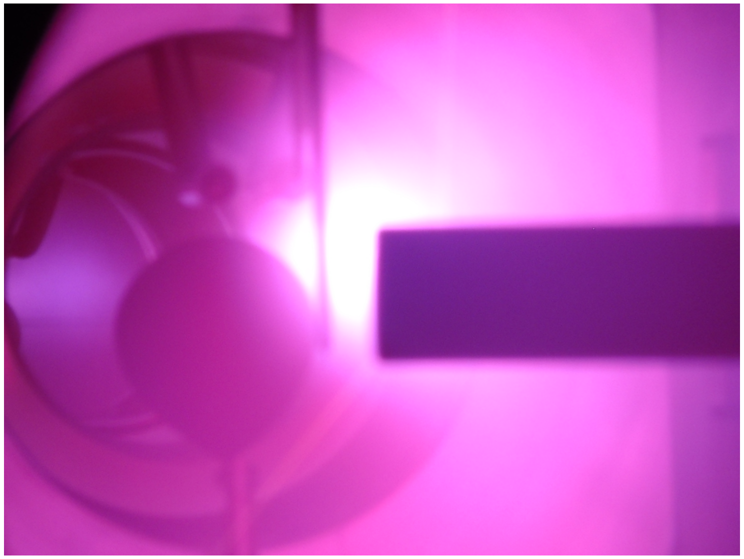
a 3D volume is reachable
stationary probes serve to register time base between shots
plots in this talk will be in xy planes at various z

Los Alamos

the plasma kink is apparent on a fast camera, having a left hand pitch as expected for J.B < 0





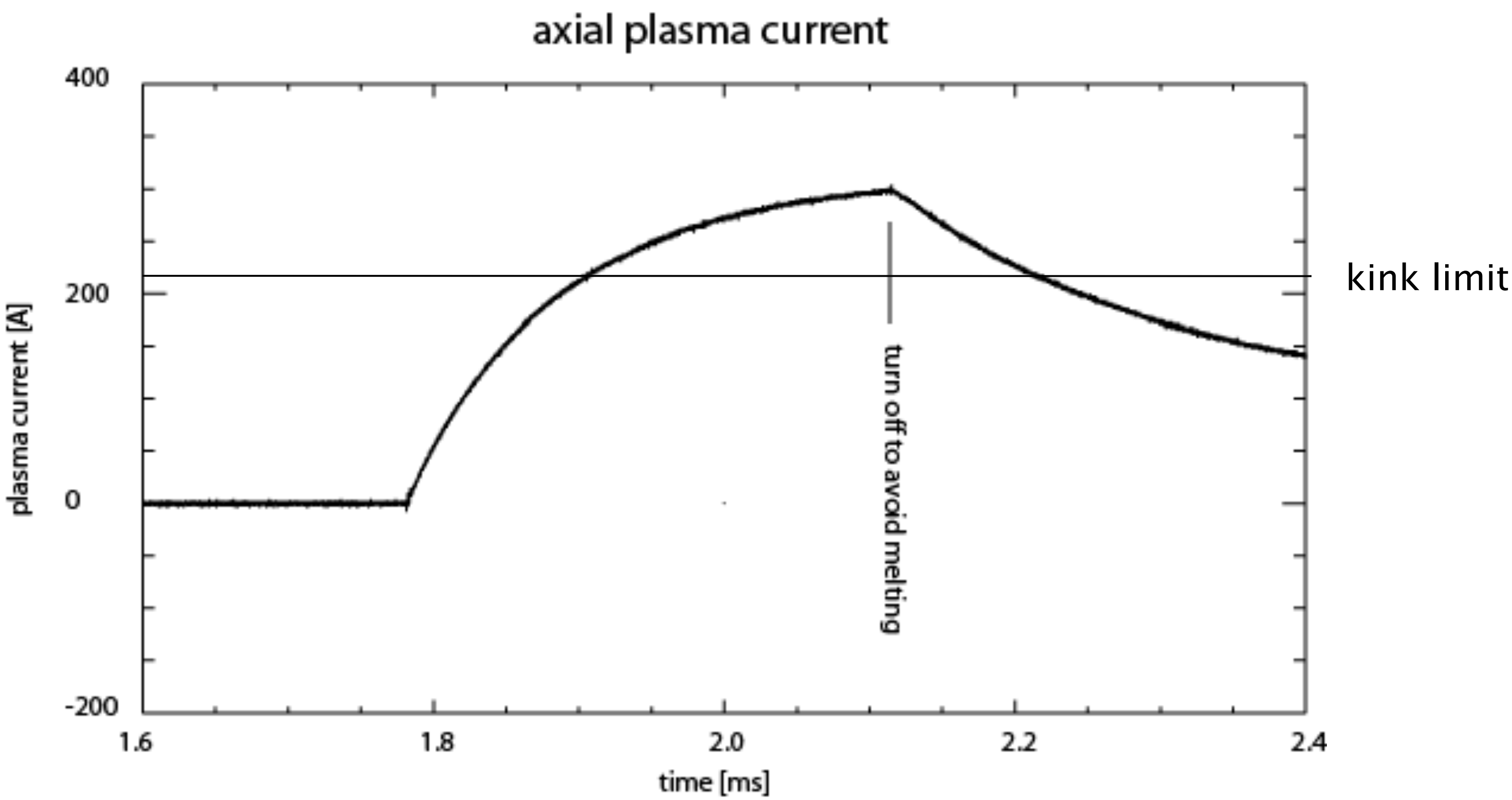


in this image:

gun
anode
scanning probe
coax gun

Los Alamos

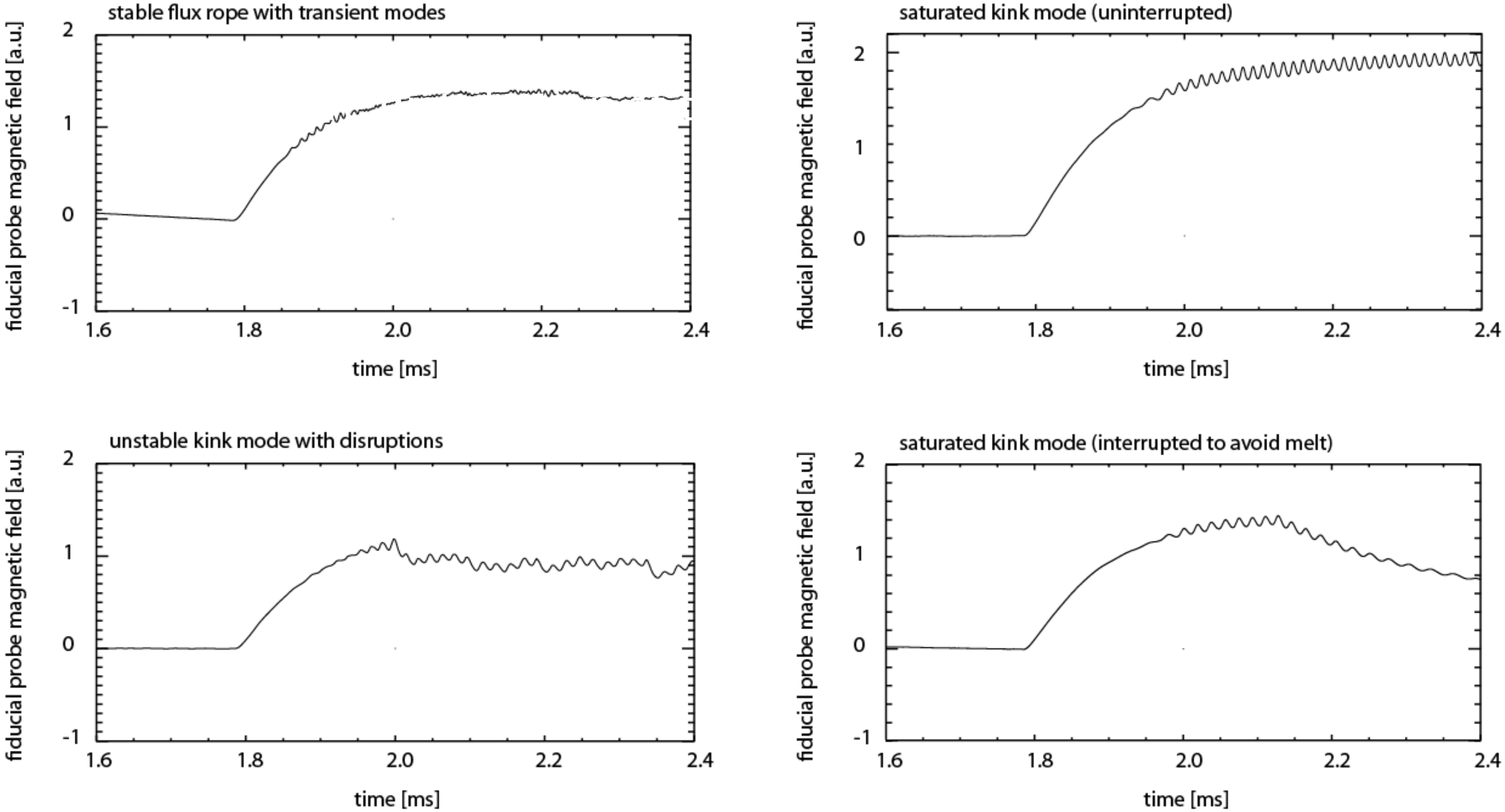
A plasma current is set up just beyond the external kink limit



axial magnetic field (300 G) is essentially static
plasma turns on at early time
plasma current drawn once discharge established
plasma current terminated early to avoid melt

Los Alamos

the flux rope can stay stable, disrupt, or attain a saturated oscillation

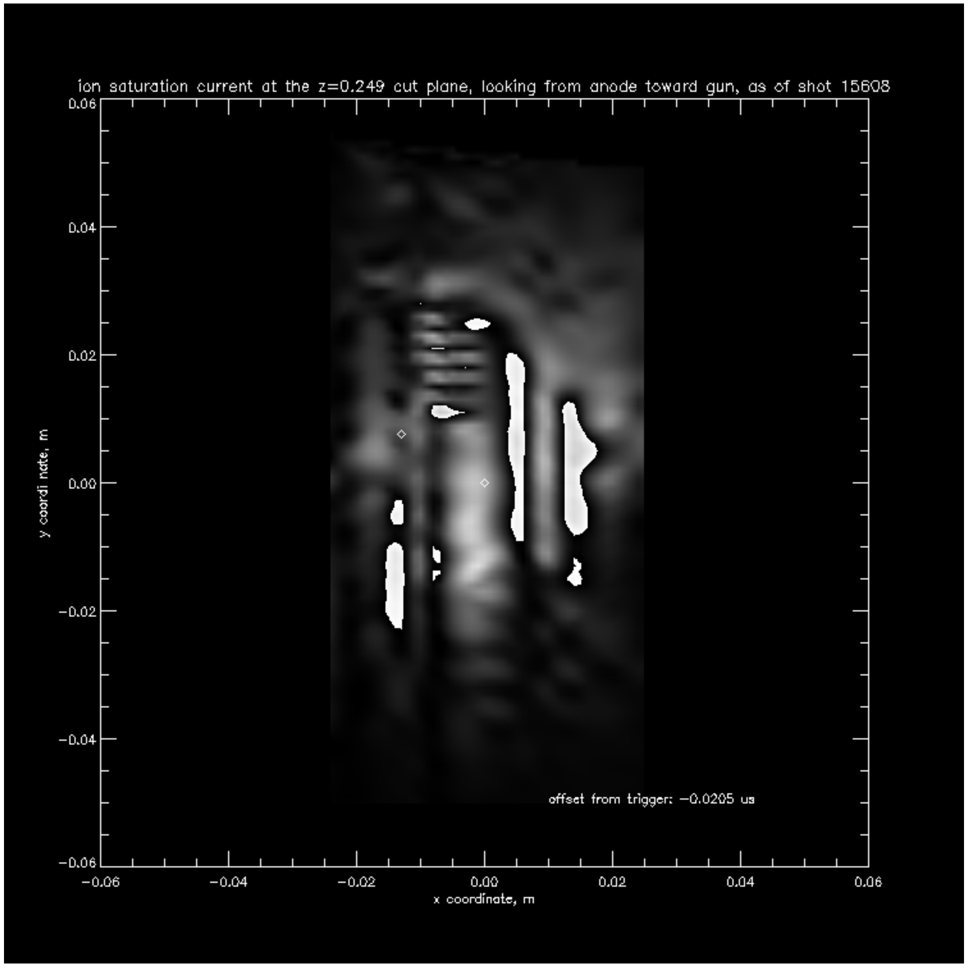


marginal stability threshold depends on line-tiedness
high frequency mode sometimes appears
disruption occurs when flux rope jumps over anode
experiment artificially shortened to avoid melt damage

conditional sampling composites structure over many repeatable discharges

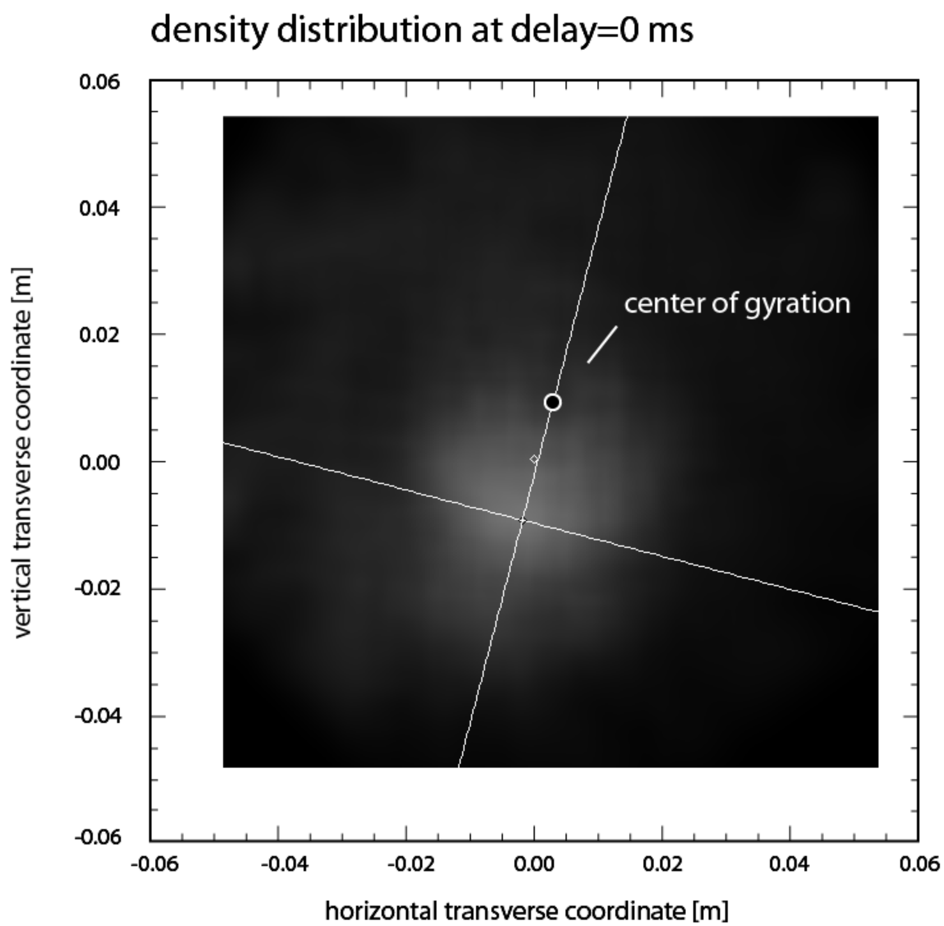
samples from failed discharges can be removed

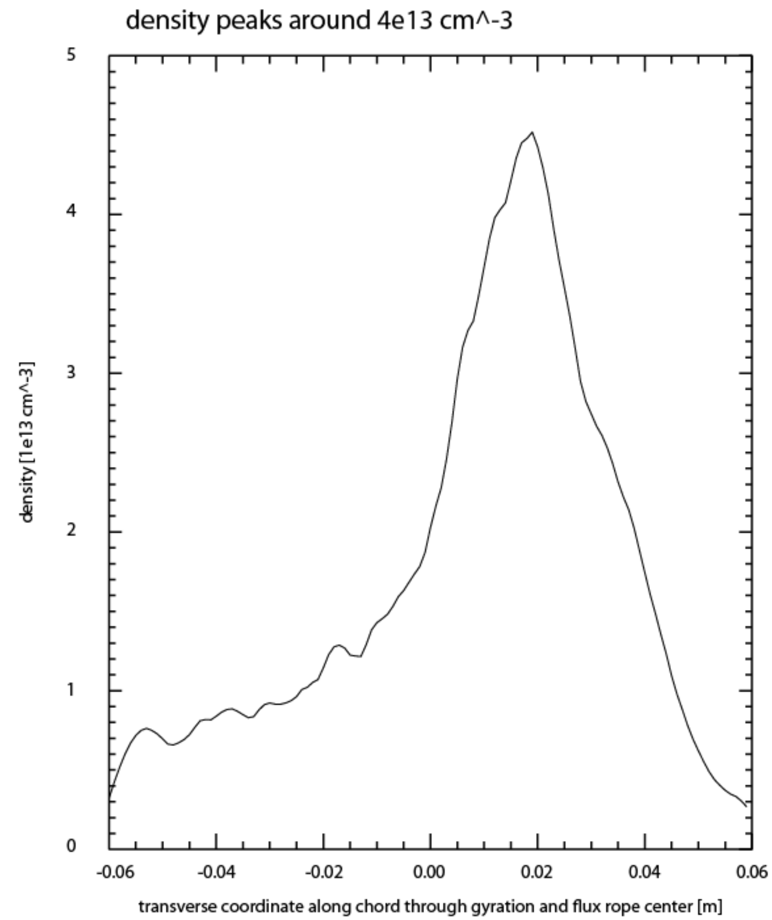
center of gyration and sense of rotation is established



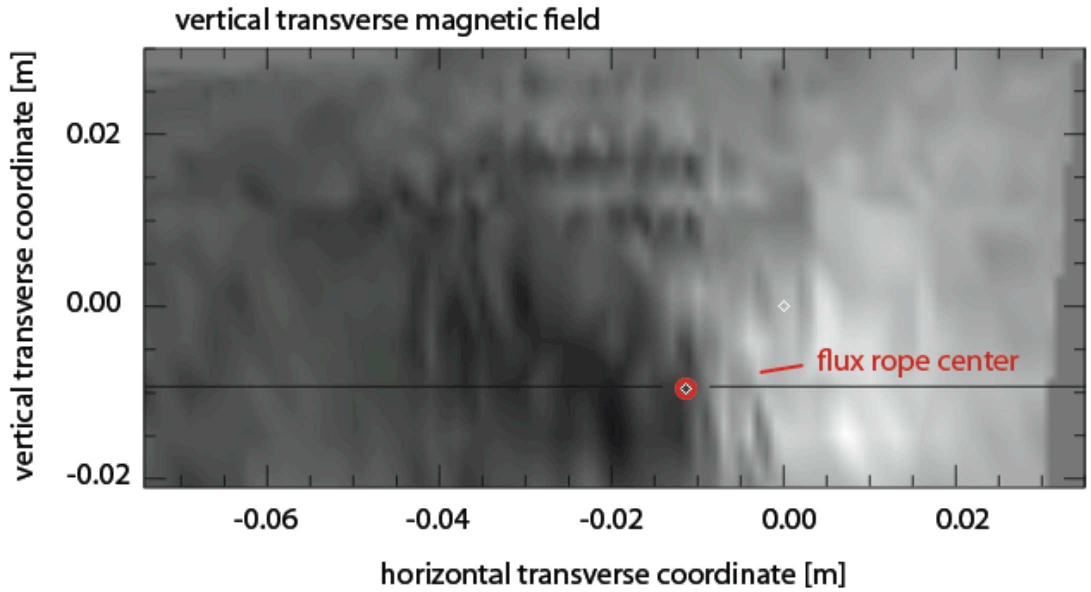
m

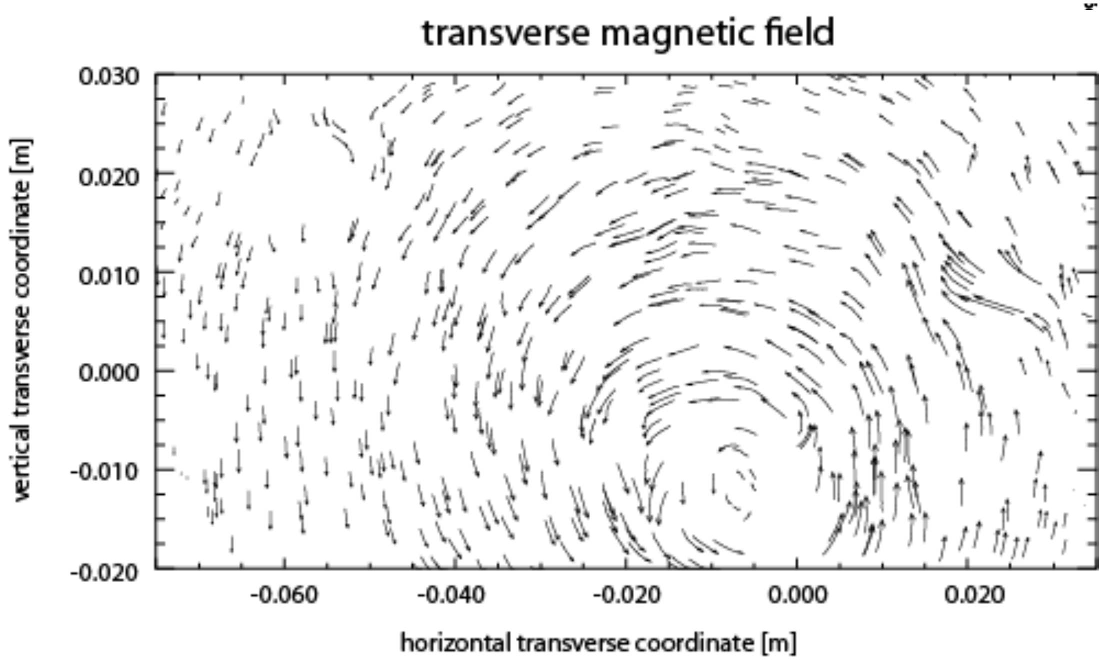
density profile peaks around 4 cm^-3 with asymmetric waist

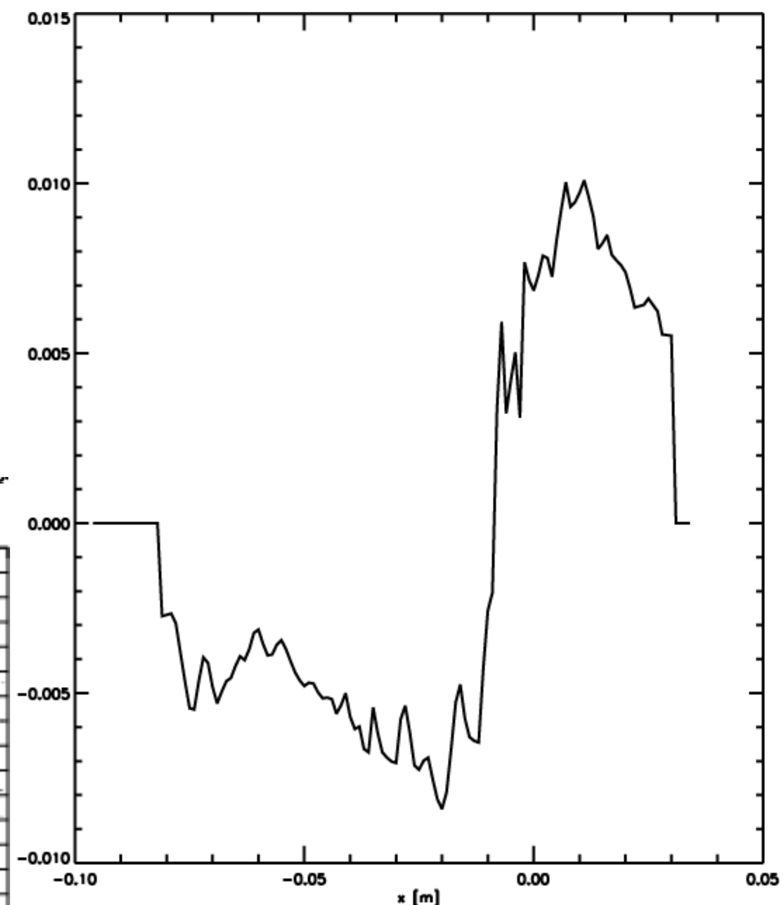




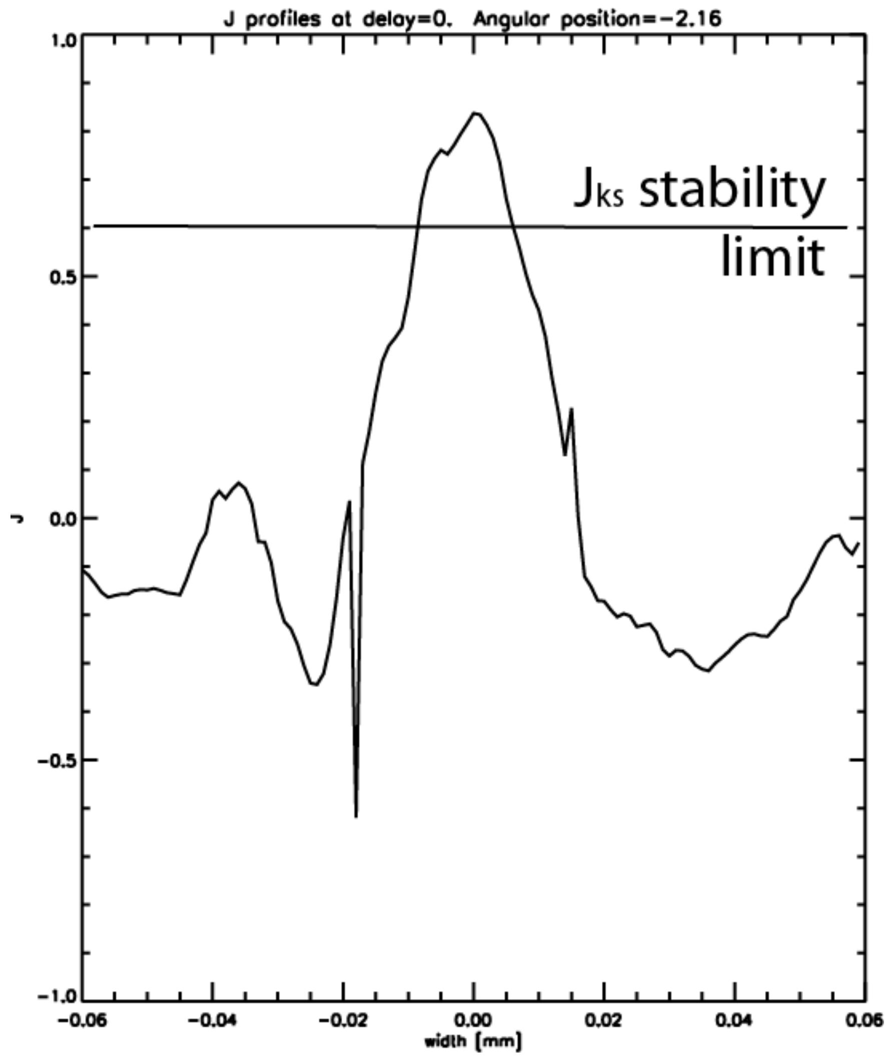
magnetic field shows characteristic peaked current density







current density is derived from B_perp. The flux rope exceeds the stability limit of 0.6 MA m^-2 for 300 G and 0.5 m

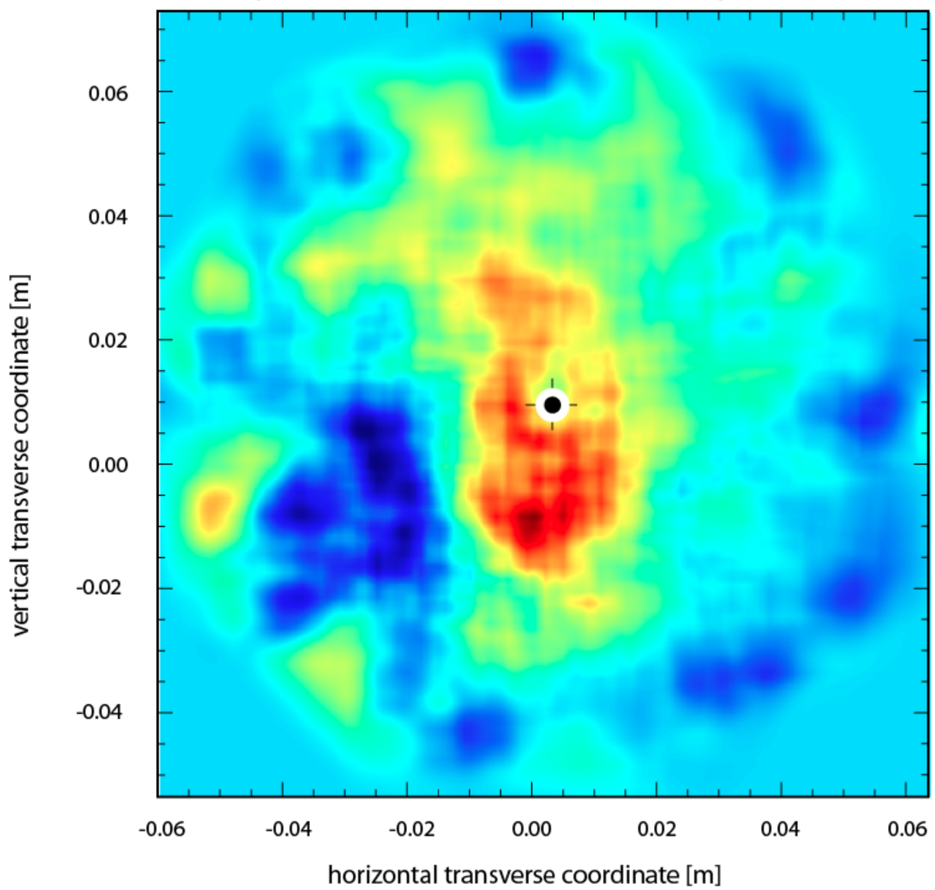


margin over stability increases with diamagnetism

Los Alamos

the difference in density between two cut planes shows the pitch of the flux rope

density difference between two cut planes



downstream density profile (blue), is rotated and at a greater radius than upstream density profile (red).

consistent with a left-hand pitch and larger kink amplitude downstream

pitch changes with z, and is different when derived from temperature (compared to density)

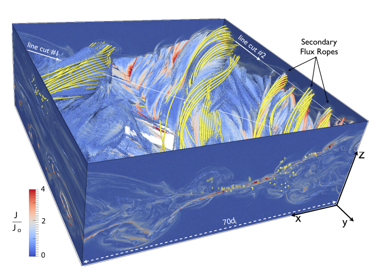
line-tiedness also affects pitch

how much affect from probe shadowing?

Los Alamos

further work vis-a-vis saturation mechanism

- B tension: untie footpoint
- flow: vary current, velocity independently
- 2 fluid: measure J, vi separately to deduce electron scale physics
- MHD simulation for non-linear effects
- VPIC simluation



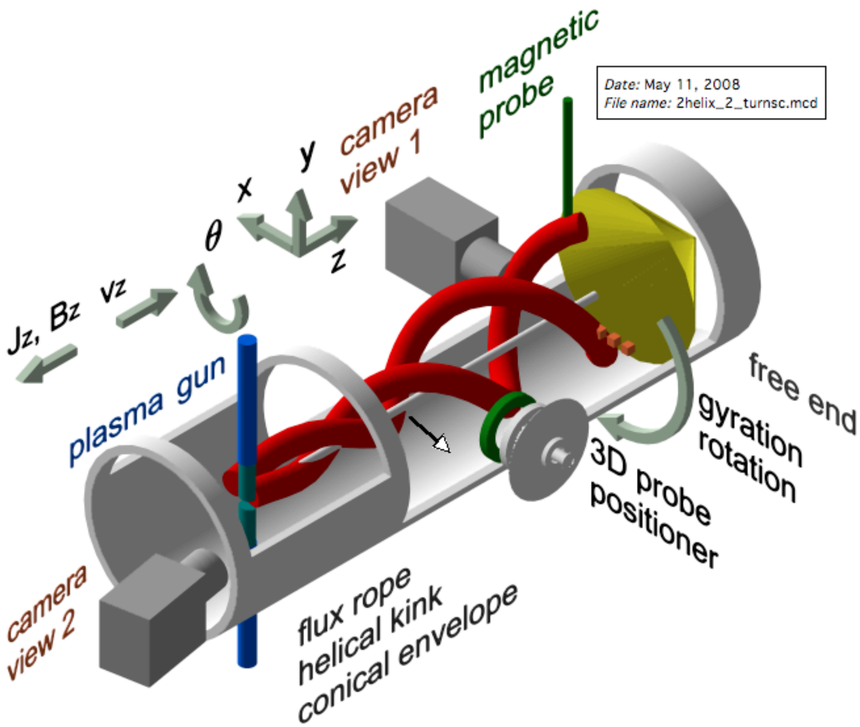
Los Alamos

End

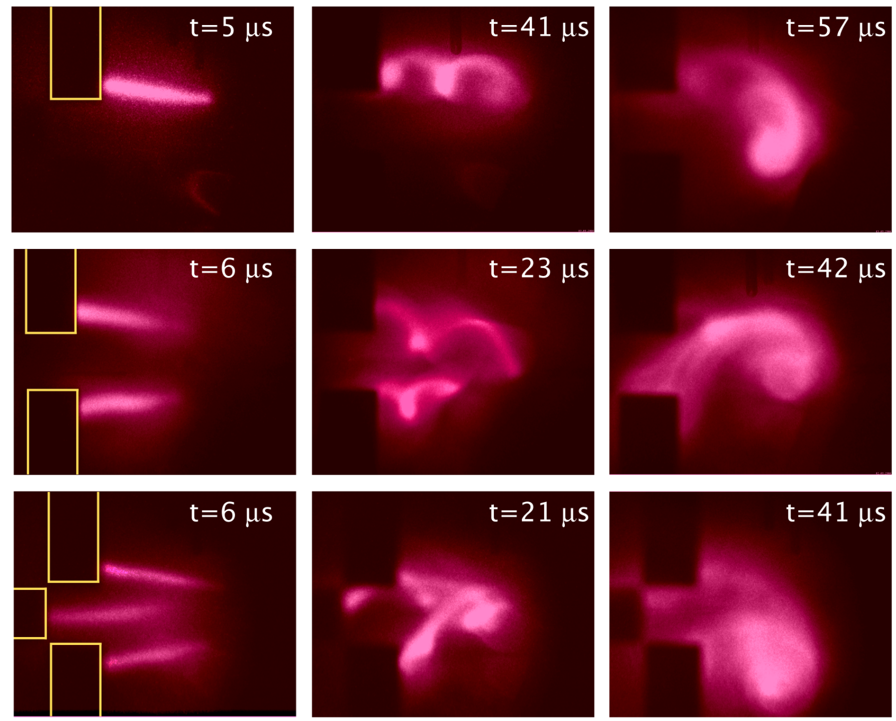
Los Alamos

RSX plasma guns generate 1, 2 or many flux ropes that kink and mutually attract

chamber and gun configuration

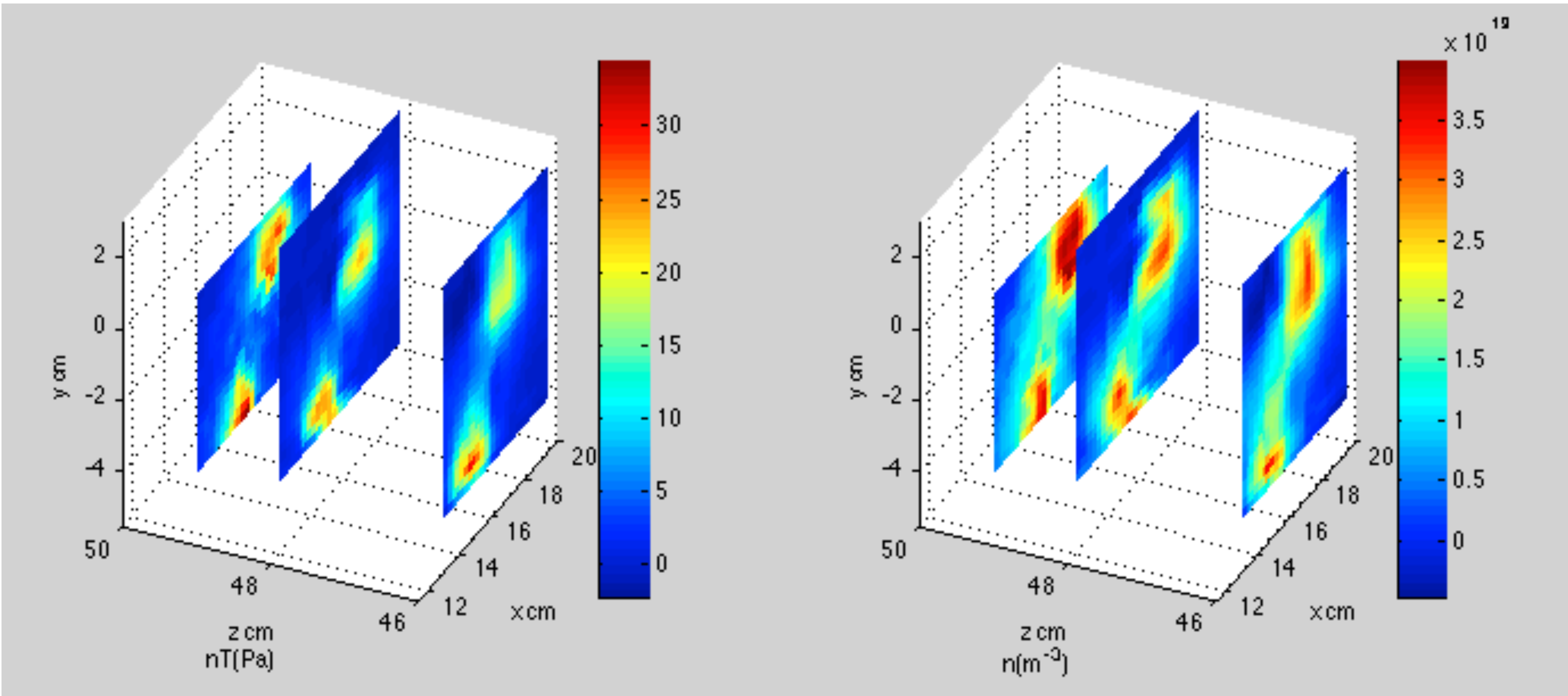


flux rope evolution



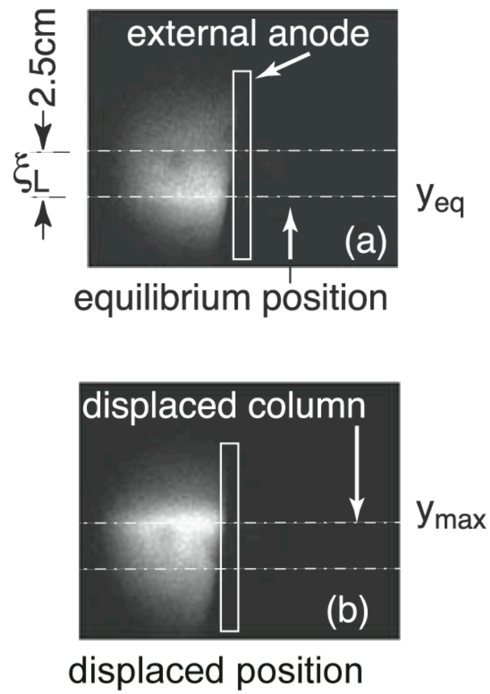
Los Alamos

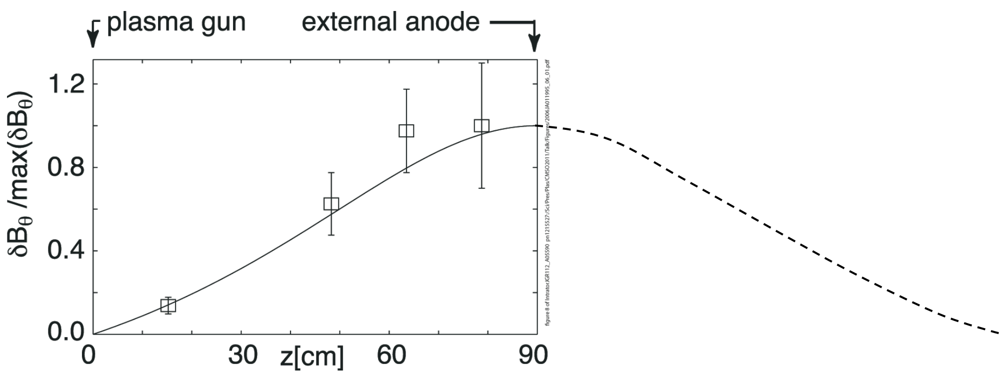
3D pressure, density profiles are reconstructed from multiple repeatable discharges

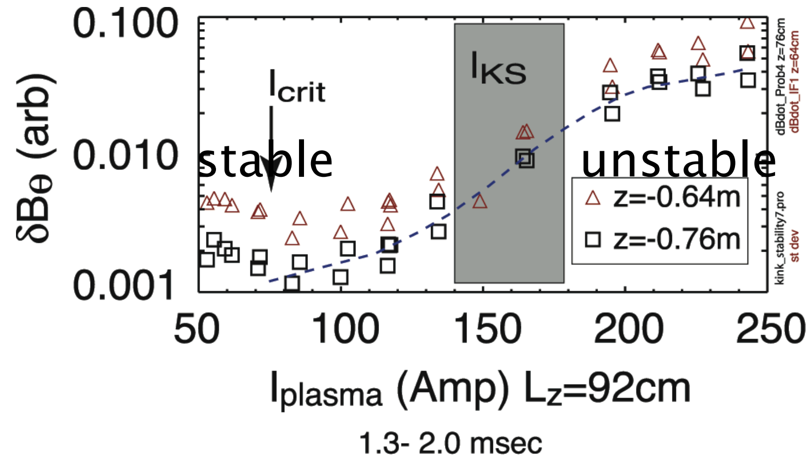


Los Alamos

a non-line-tied footpoint due to sheath resistivity reduces the instability current limit



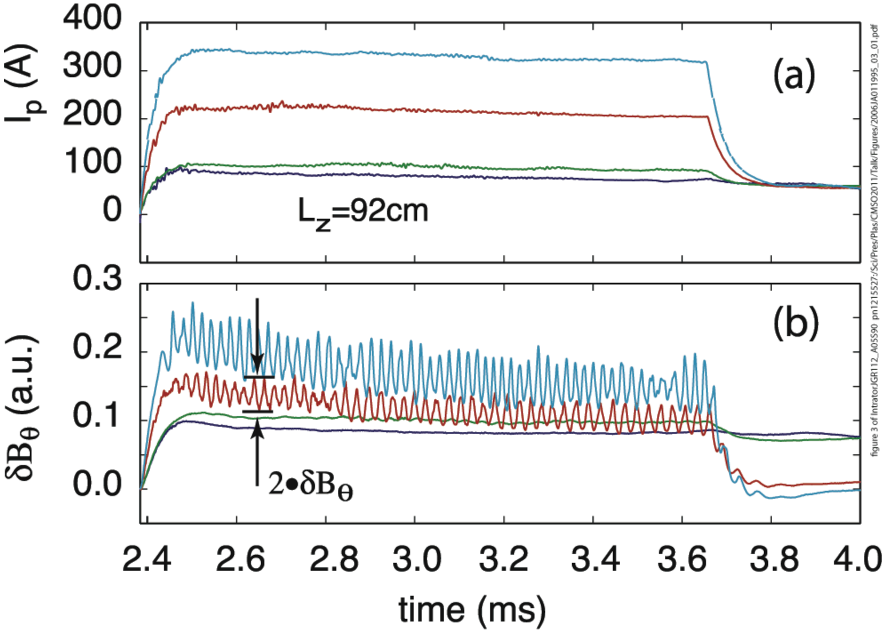


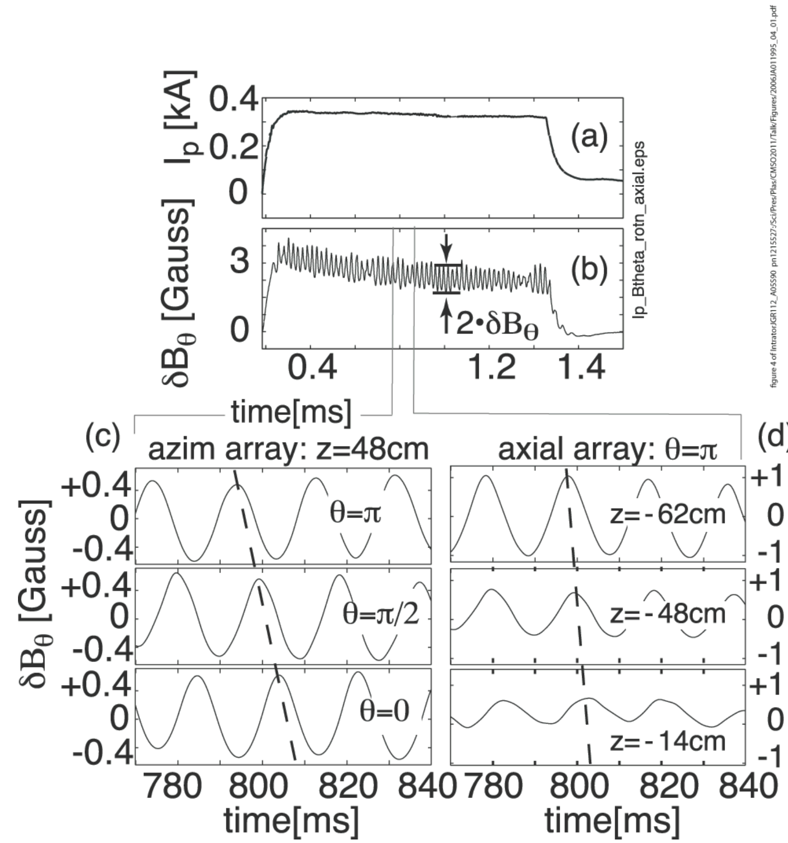


IntratorJGR2007

Los Alamos

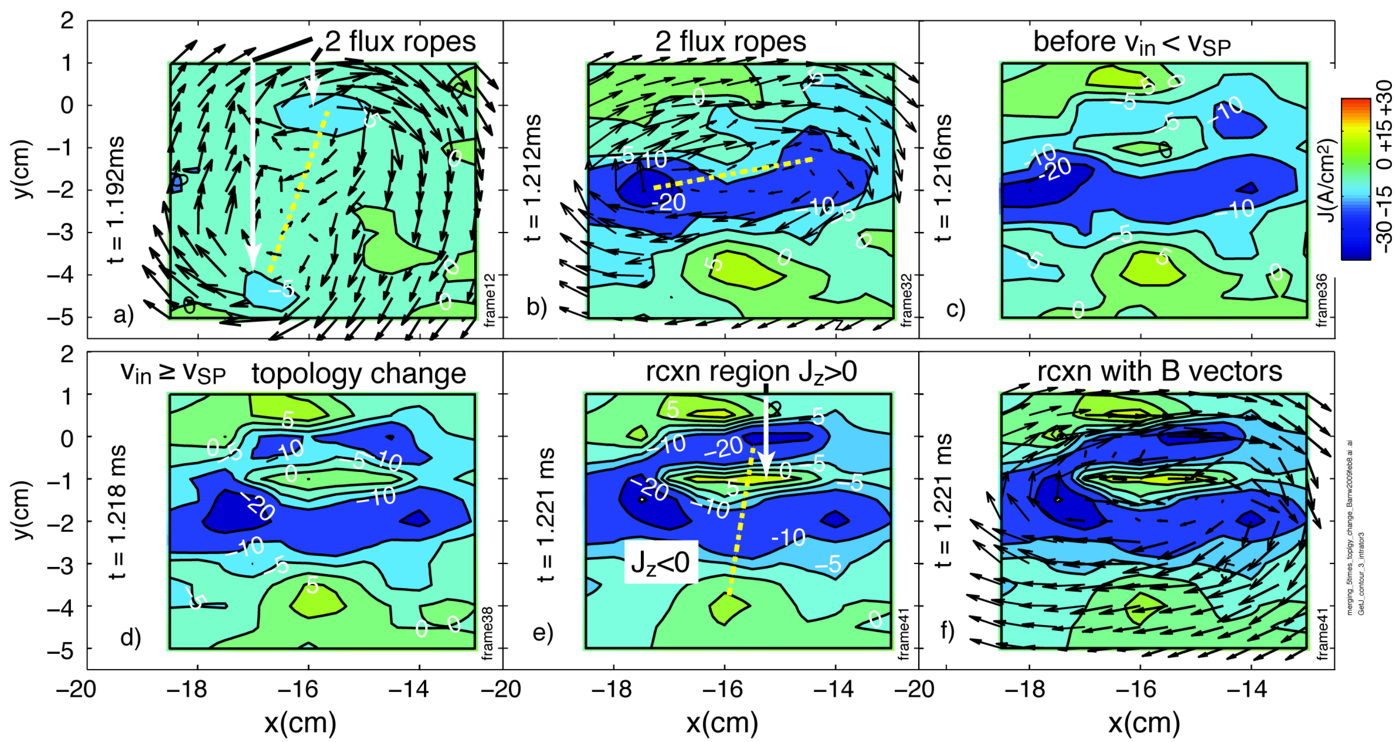
flux rope kinks and gyrates at a threshold below the kruskal-shafranov limit





Flux pileup and reconnection develop when $v_{inflow} > v_{Sweet\ Parker}$

B, Jz contours



B_z = 100 G

B_θ = 10 G

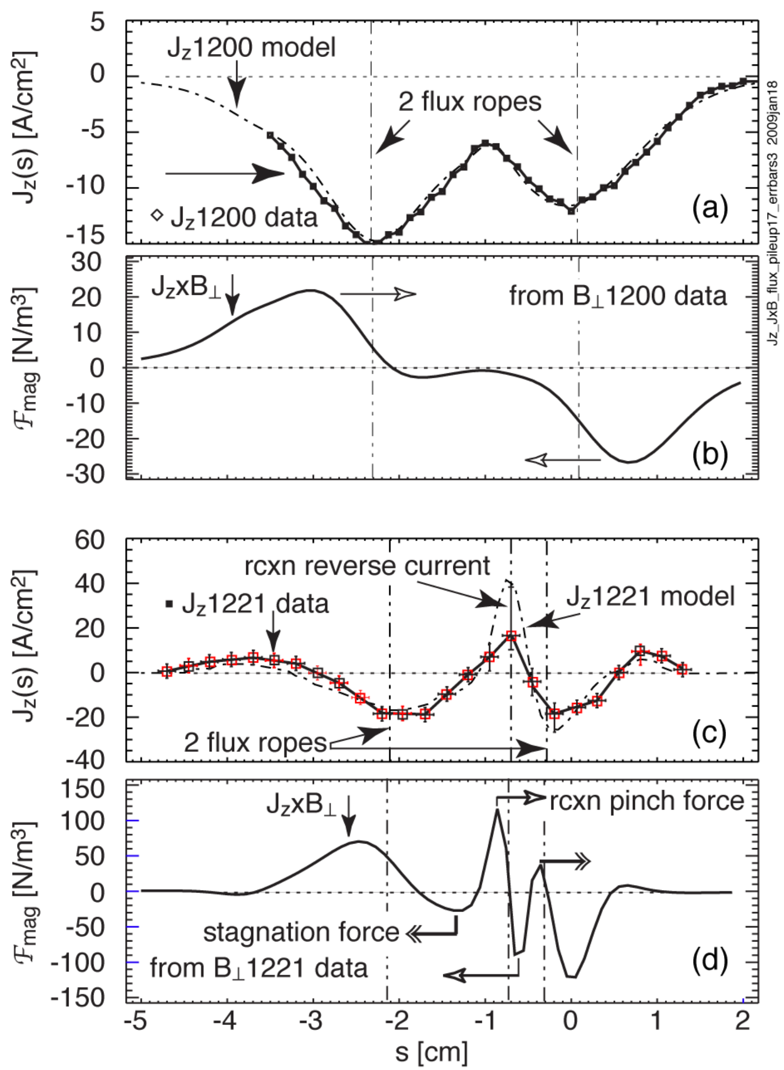
z = 0.48 m

Intrator, Nature Phys. 5, 521

Los Alamos

JxB forces repel incoming flux ropes

- approach velocity above Sweet-Parker speed yields reconnection
- JxB pinch: reconnection current sheet (hollow arrow ≈ 100N/m³)
- JxB repulsion (double fleche ≈ 30N/m³) stalls merging

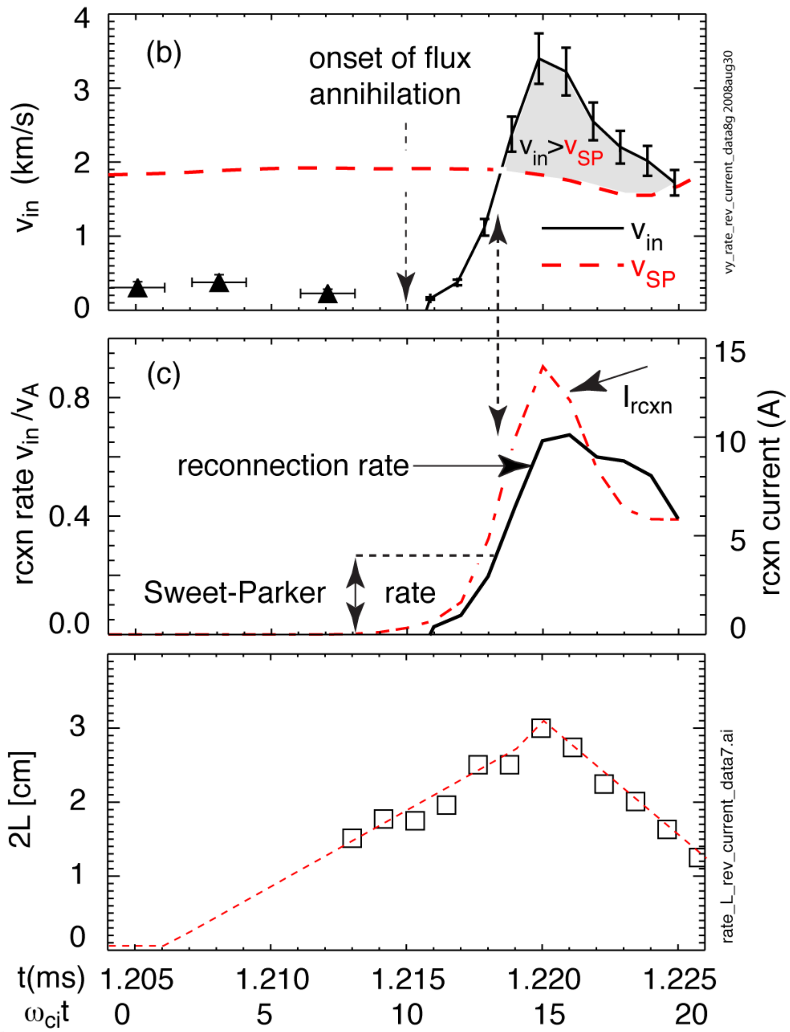


before reconnection

during reconnection

Los Alamos

Reconnection when $v_{inflow} > v_{SP} = v_A / S^{1/2}$

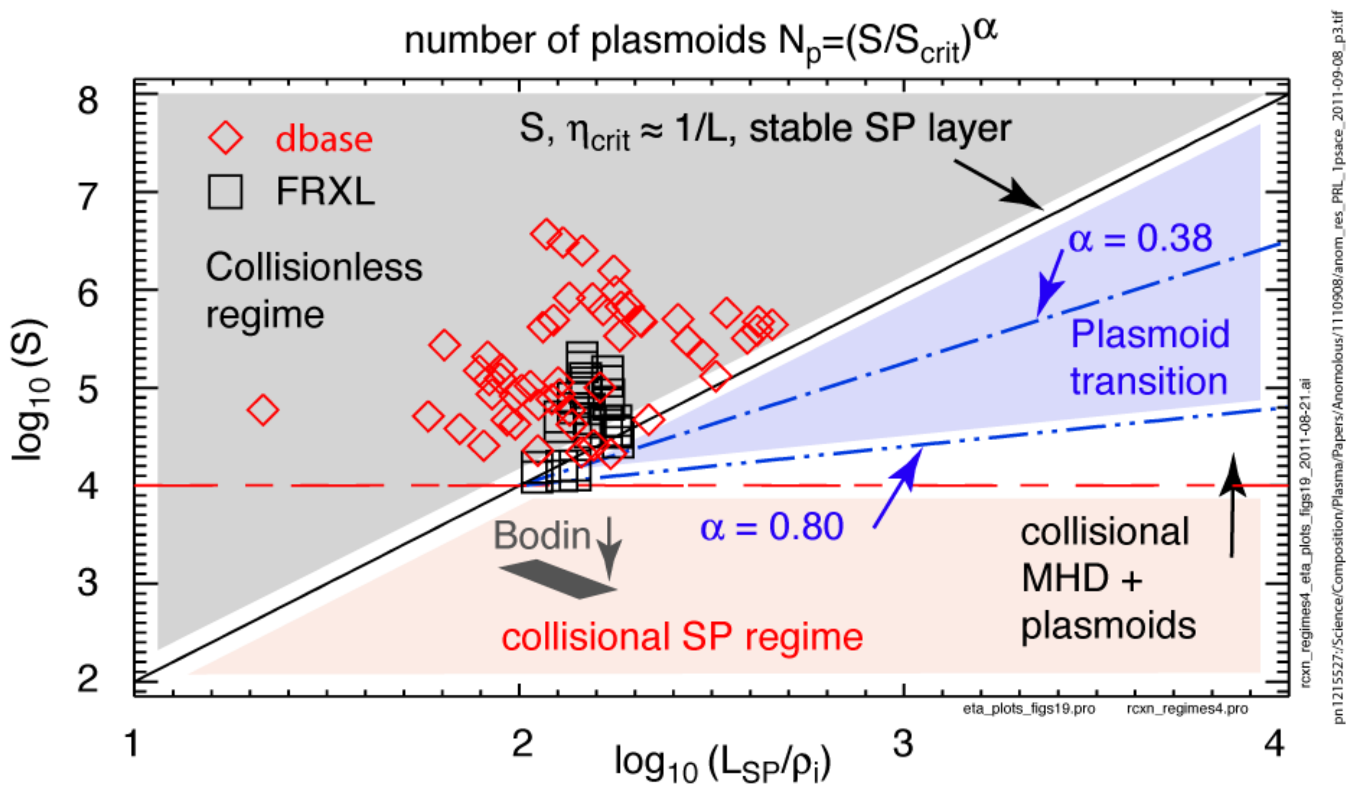


Intrator, Nature Phys. 5, 521

- define reconnection boundary where:
  - J_z, E_z(total during rcxn) changes sign
- at the edge of reconnection region find evolution of
  - $v_{in} \approx E_{z,tot}/B_\perp$
  - rate = v_{in} /vA at the edge
  - length 2L of rcxn region

Los Alamos

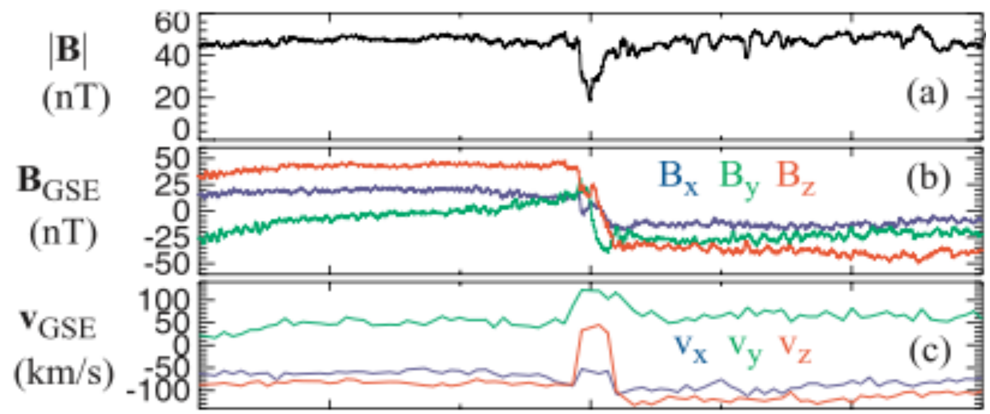
RSX parameter space in the collisional regime; FRCs complement with plasmoid transition/ collisionless regime



Los Alamos

Evidence in lab and in nature suggests our existing 2D models are not complete

magnetopause reconnection $v_{in} \sim 0.07 v_A$ (fast)



Phan GRL34 Cluster-1

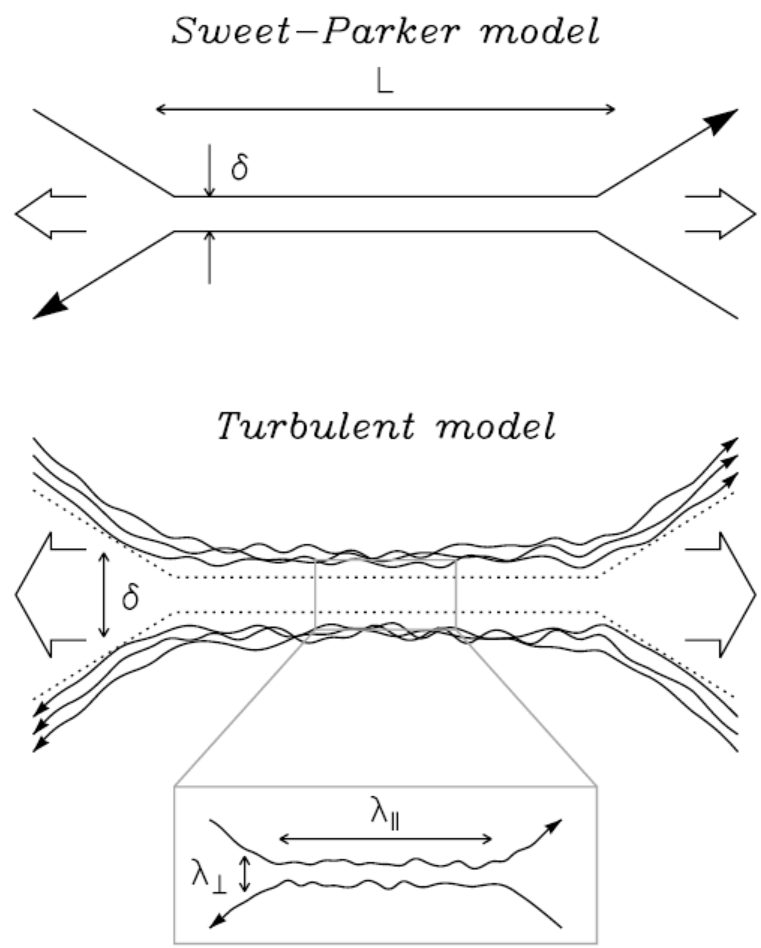
reconnection is faster, on larger scale, than models predict; solutions (Petschek, Hall, Lazarian/Vishniac) resort to:

- modified resistivity and/or
- introduction of small-scale structure

Los Alamos

Turbulent reconnection, with inherent small scale structure, is rendered in RSX

Turbulence couples flows and magnetic structure across all scales



Los Alamos

Reconnection Scaling Experment (RSX)

flux rope as reconnection prototype

Turbulent reconnection, with inherent small scale structure, is rendered in RSX

anatomy of turbulence at dissipation scale

finite length x-lines, 3D null points, or quasiseparatrices

geometry, inflow depend on turbulence scaling, not global geometry

onset and termination of reconnection can be unsteady or explosive

Los Alamos

Turbulent reconnection, with inherent small scale structure, is rendered in RSX

anatomy of turbulence at dissipation scale

finite length x-lines, 3D null points, or quasiseparatrices

geometry, inflow depend on turbulence scaling, not global geometry

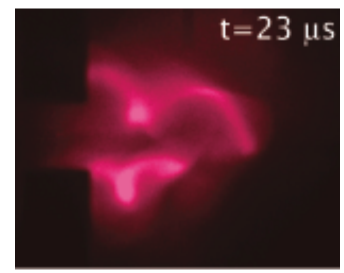
onset and termination of reconnection can be unsteady or explosive

congruent RSX attribute

3D, aperiodic contact between flux ropes

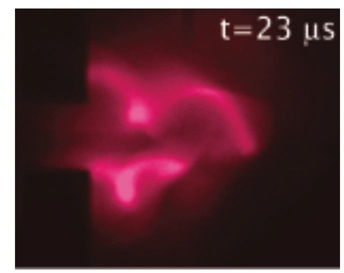
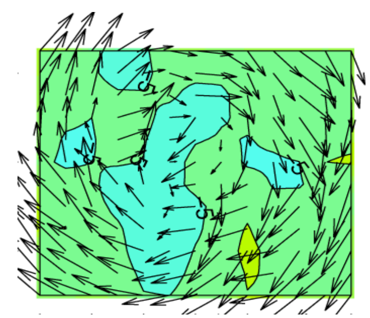
Los Alamos

Turbulent reconnection, with inherent small scale structure, is rendered in RSX

anatomy of turbulence at dissipation scale	congruent RSX attribute	
finite length x-lines, 3D null points, or quasiseparatrices	3D, aperiodic contact between flux ropes	
geometry, inflow depend on turbulence scaling, not global geometry	unprogrammed kinking, variably line-tied BCs	
onset and termination of reconnection can be unsteady or explosive		

Los Alamos

Turbulent reconnection, with inherent small scale structure, is rendered in RSX

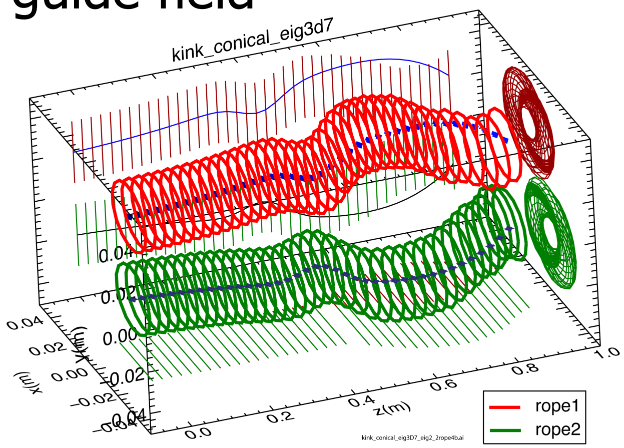
anatomy of turbulence at dissipation scale	congruent RSX attribute	
finite length x-lines, 3D null points, or quasiseparatrices	3D, aperiodic contact between flux ropes	
geometry, inflow depend on turbulence scaling, not global geometry	unprogrammed kinking, variably line-tied BCs	
onset and termination of reconnection can be unsteady or explosive	colliding flux ropes merge, bounce, or erratically tear	

Los Alamos

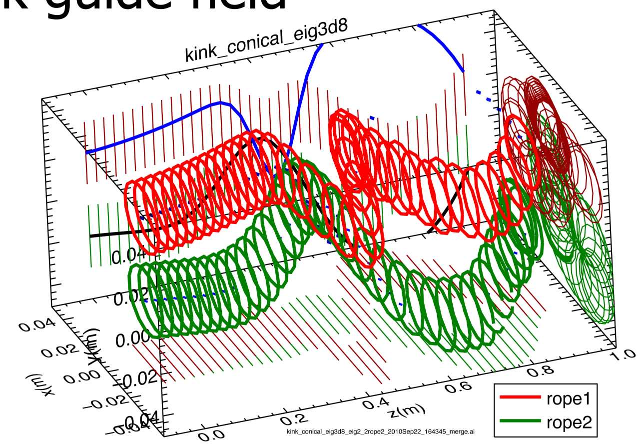
unprogrammed flux rope evolution samples competing forces self-consistently

kink eigenfunction reconstructions

strong guide field



weak guide field



unprogrammed flux rope evolution samples competing forces self-consistently

coalescence is governed by:

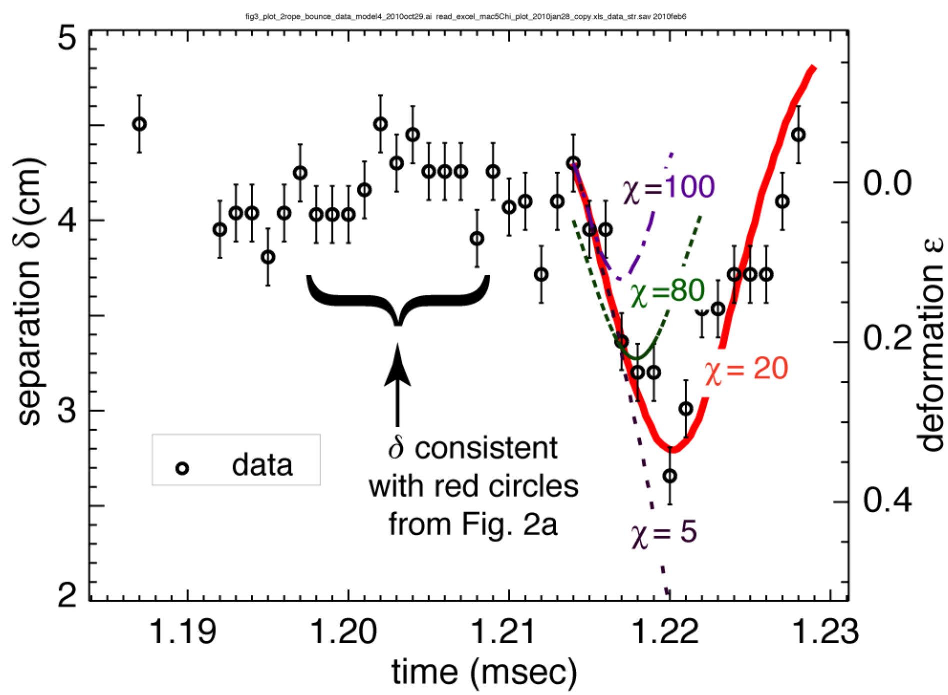
- line-tiedness of footpoints (axial boundary conditions)
- Kruskal-Shafronov instability (kink)
- parallel current attraction
- flux and pressure pileup

unprogrammed flux rope evolution samples competing forces self-consistently

coalescence is governed by:

- line-tiedness of footpoints (axial boundary conditions)
- Kruskal-Shafronov instability (kink)
- parallel current attraction
- flux and pressure pileup

modeling of flux rope deformation matches observation



single flux rope dynamics

what next?

Los Alamos

further turbulent features to explore:

propagation (zippering) of the reconnection patch

---

is entropy conserved along reconnecting field line?

---

forced footpoint perturbation (tearing mode)

---

characterize flow streamlines via field structure

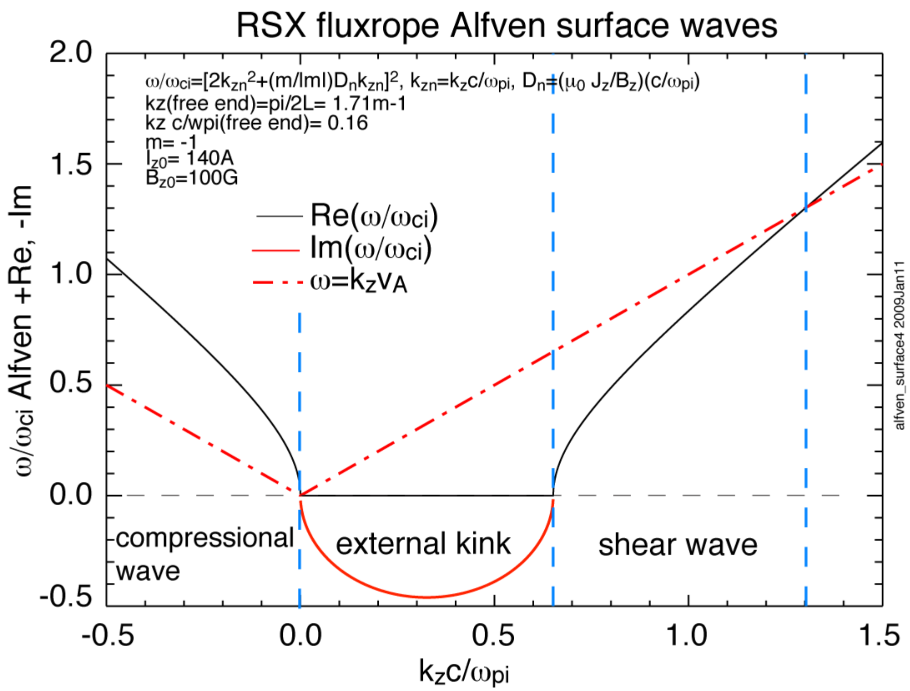
---

saturation of kink instability for many gyrations

Los Alamos

further turbulent features to explore:

Correlate spectral signatures with direct probing of reconnection region (application to space craft data interpretation)



Example: reconnection diffusion layer contains reversed current J_z:

Is mode conversion outside diffusion layer mediated by kink?

Los Alamos

Summary

RSX is a flexible testbed for the fundamental unit of turbulent reconnection

- diagnostic resolution beyond electron skin depth (dissipation) scale
- aperiodic reconnection patch has 3D nulls or QSLs
- interaction of variably line-tied flux ropes is undriven
- variable fates observed at collision site: merge, bounce or erratic tearing
- flux rope dynamics are important
- novel features of reconnection to be explored (spectral signature, propagation, entropy conservation, footpoint forcing, streamline characterization)

Los Alamos